Combined Swarm/Sentinel Gravity Fields

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Sentinel-1

Sentinel-2

Sentinel-3

Courtesy: ESA

Introduction

- Gravity fields derived from Swarm GPS data are considered important for bridging the upcoming gap between the dedicated gravity satellite missions GRACE and GRACE-FO.
- Currently, the constellations of the first three Sentinel missions of **ESA's Copernicus Earth observation program** are being established with the last successful launch of Sentinel-2B on March 7, 2017 from Kourou. There are now five Sentinels in Low Earth Orbits (LEOs), see Table 1.
- Each Sentinel satellite is equipped with GPS receivers (same manufacturer as for Swarm) and star cameras, allowing for the Precise Orbit Determination (POD) of the satellites with cm accuracy.
- At the Astronomical Institute of the University of Bern both (reduced-) dynamic and kinematic orbits are computed using the Bernese GNSS Software v5.3. For kinematic POD the three-dimensional position of the satellite and the receiver clock correction are estimated at every observation epoch. Since kinematic orbits are fully independent of any dynamics and force models used for LEO POD, they are suitable for a subsequent recovery of the Earth's gravity field.
- We present the quality of the Sentinel-1A, -2A, and -3A (S1A, S2A, S3A) kinematic orbits up to end of 2016.
- We employ the Celestial Mechanics Approach (CMA, Beutler et al., 2010) to compute monthly and static gravity fields from these kinematic orbits, as well as their combination with the corresponding Swarm gravity fields.

Satellite	Launch date	Altitude	Inclination	Months
S1A	03 Apr 2014	692 km	98.2°	33
S1B	25 Apr 2016	693 km	98.1°	
S2A	23 June 2015	786 km	98.6°	18
S2B	07 Mar 2017	n/a	n/a	
S3A	16 Feb 2016	800 km	98.6°	10
Swarm-A/C	22 Nov 2013	452 km	87.4°	36
Swarm-B	22 Nov 2013	503 km	87.7°	36

Table 1: Sentinel (and Swarm) satellites so far in orbit with their average altitudes (semi-major axis minus Earth radius at equator) and inclinations. The satellites with shaded entries were used for this study, the last column indicates the number of months included.

Kinematic Orbits

Figure 1 shows the daily carrier phase residuals for the Sentinel and Swarm kinematic POD. For Sentinel maneuver days have been excluded (214 days for S1A, 20 for S2A, and 16 for S3A). A clear correlation with the Total Electron Content (TEC) in the ionosphere is visible.

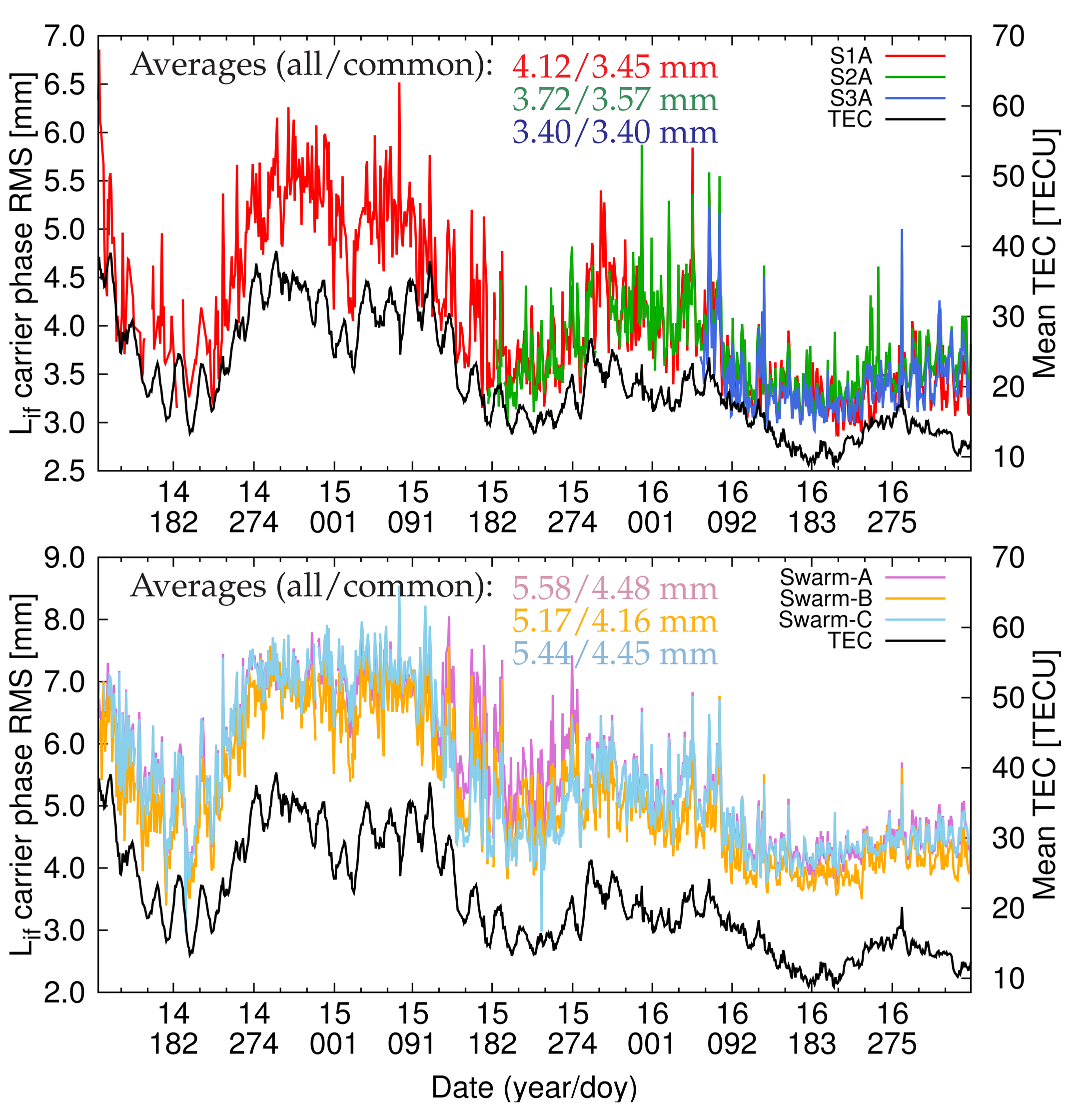


Figure 1: Daily RMS values of the ionosphere-free carrier phase residuals of kinematic POD in mm for Sentinel (top) and Swarm (bottom), and the mean TEC values (black) in units of TECU (1 TECU$\equiv 10^{16}$ electrons/m^2) for the entire time span considered. The 2nd displayed average values are valid for the common period 16 Feb - 31 Dec 2016.

Figure 2 shows that, unlike for Swarm, the carrier phase residuals of S1A do not show signatures along the geomagnetic equator for a period of high ionospheric activity and similar orbit geometry.

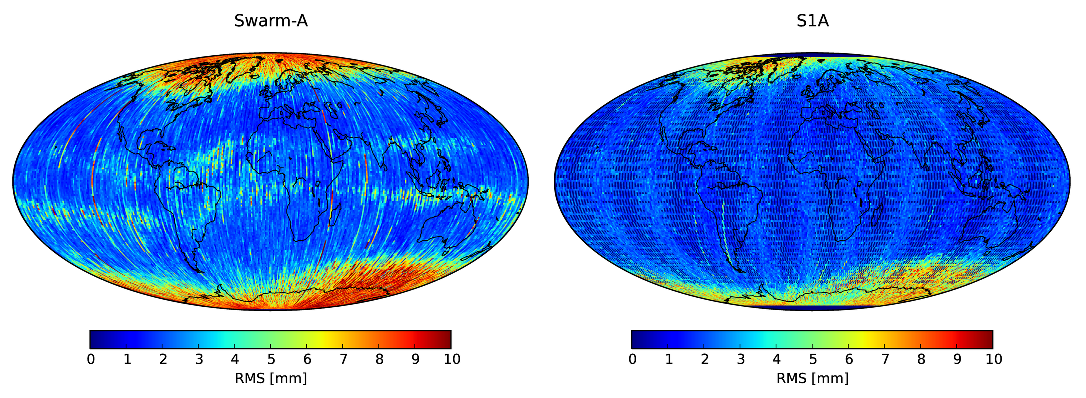


Figure 2: Geographically binned RMS values of ionosphere-free GPS carrier phase residuals of Swarm-A (left) and S1A (right) kinematic POD covering the time span Nov-Dec 2014. The angles β of the Sun above orbital planes are $-72.3° \leq \beta \leq -34.7°$ for Swarm-A and $75.1° \leq \beta \leq 82.6°$ for S1A.

Of the three Sentinel LEOs considered only S3A is equipped with a retroreflector for Satellite Laser Ranging (SLR). Figure 3 shows the SLR residuals, i.e., the differences between the computed and the measured range, of the S3A kinematic orbits. 15 SLR stations have been included and an outlier threshold of 30 cm applied, resulting in a total number of 37990 SLR normal points.

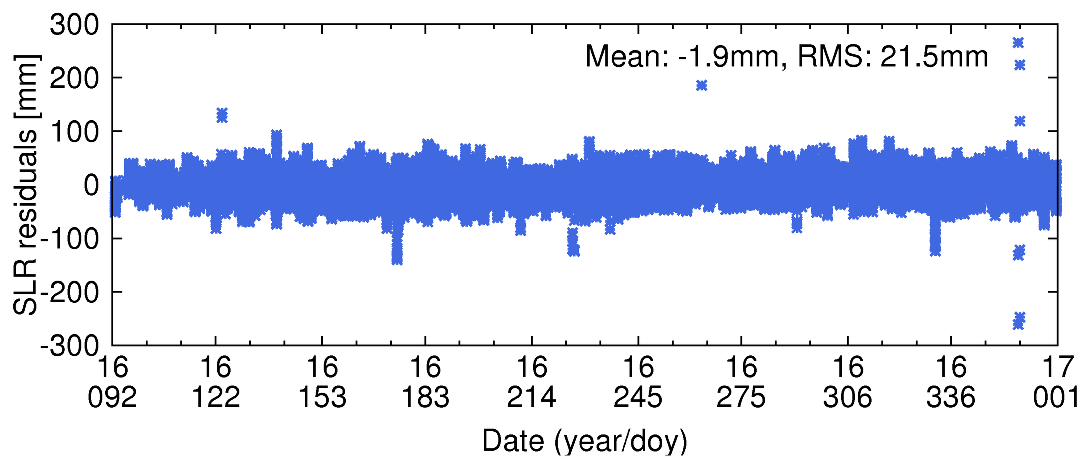
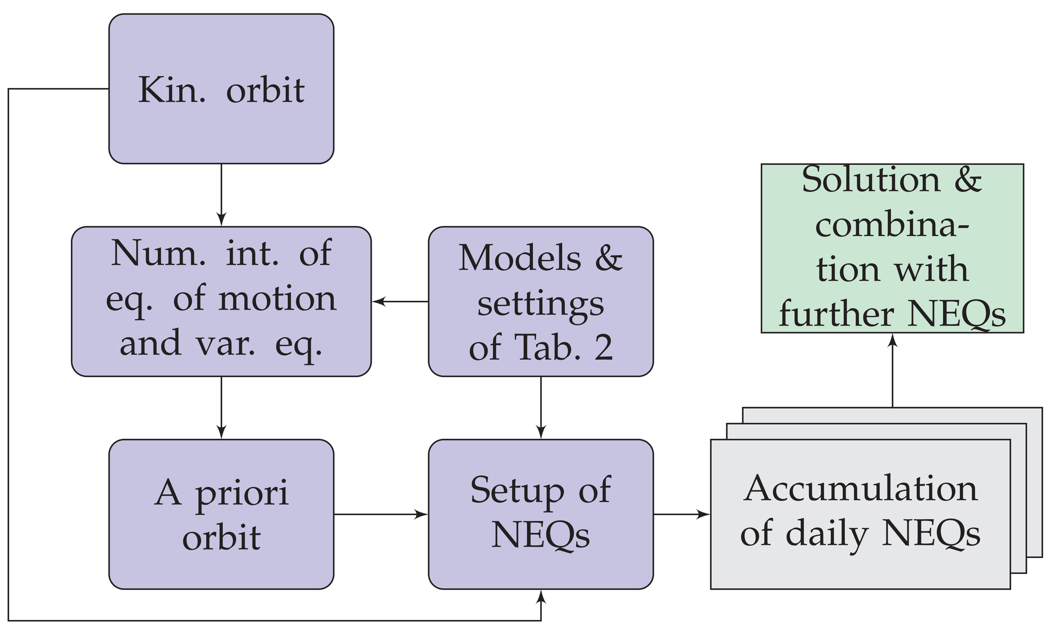


Figure 3: SLR residuals of the kinematic S3A orbits for the entire time span considered (S3A was tracked by SLR from 01 Apr 2016 on) without maneuver days.

SLR observations can also be used to estimate systematic orbit offsets by minimizing the SLR residuals in a least-squares adjustment. Using the above SLR observations, an estimation of an orbit offset over the entire time span yields -2.1 ± 0.4 mm, -6.7 ± 0.5 mm, and 3.5 ± 0.5 mm in radial, along-track, and cross-track direction, respectively.

The Celestial Mechanics Approach

The kinematic orbits of S1A, S2A, and S3A, as well as the corresponding kinematic orbits of the three Swarm satellites serve as pseudo-observations for the CMA of gravity field recovery. The epoch-wise covariance information of the kinematic positions is introduced for the weighting. Normal Equations (NEQs) are set up for the parameters listed in Tab. 2:



A priori gravity model	AIUB-GRACE03S (Jäggi et al., 2012), d/o 70
Ocean tides	EOT11a
Atm. & ocean de-aliasing	AOD1B RL05
Ocean pole tides	Desai, 2002
Tide system	Tide-free
Arc length	24 h
Data sampling	10 s
Initial state vector	1/arc
Empiricals	Const. and 15 min piecewise-const. acc. in radial, along-track, cross-track dir.
Gravity field parameters	Spherical harm. coeff. to d/o 70

Table 2: Models and parameters employed and estimated in the CMA for the gravity recovery.

Gravity Field Results

Figure 4 shows difference degree amplitudes of Sentinel and Swarm gravity fields, when leaving out the SH coefficients most affected by a polar gap of 8° (see Tab. 1) according to van Gelderen and Koop (1997).

For the other coefficients, up to degrees of approximately 10-15 the kinematic orbits of the Sentinel LEOs can contribute to the Earth gravity field recovery on the same level as the Swarm LEOs.

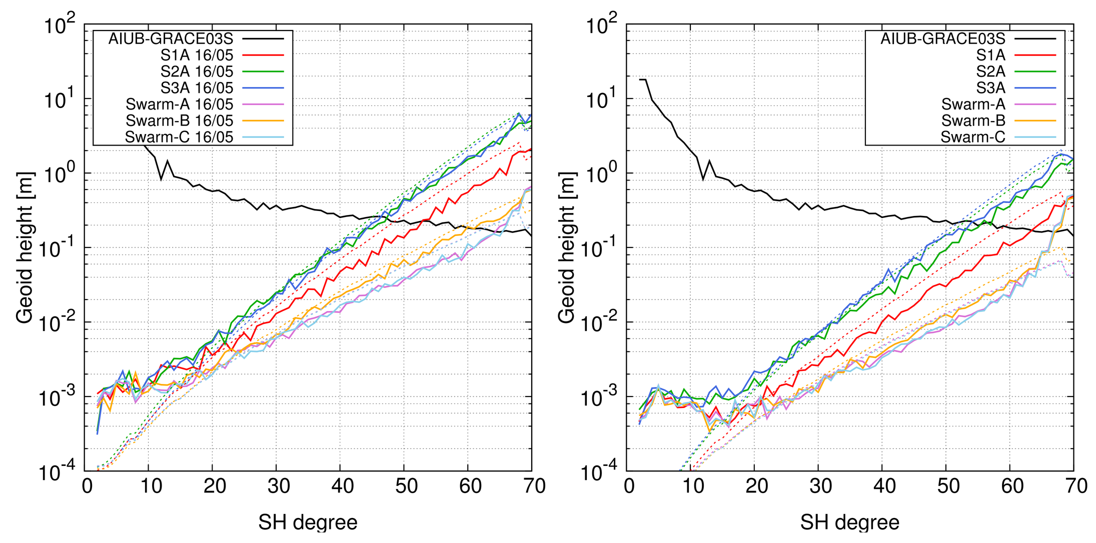


Figure 4: Difference degree amplitudes (solid) and formal error degree amplitudes (dashed) of Sentinel and Swarm gravity fields for May 2016 (left) and for the entire time span of 33 months for S1A, 18 months for S2A, 10 months for S3A, and 36 months of Swarm (right).

For periods with high ionospheric activity, the Swarm GPS data prior to May 2015 requires significant screening. This degrades the lowest degrees of the Swarm gravity fields (Jäggi et al., 2016). The addition of Sentinel data is beneficial (see also Fig. 2):

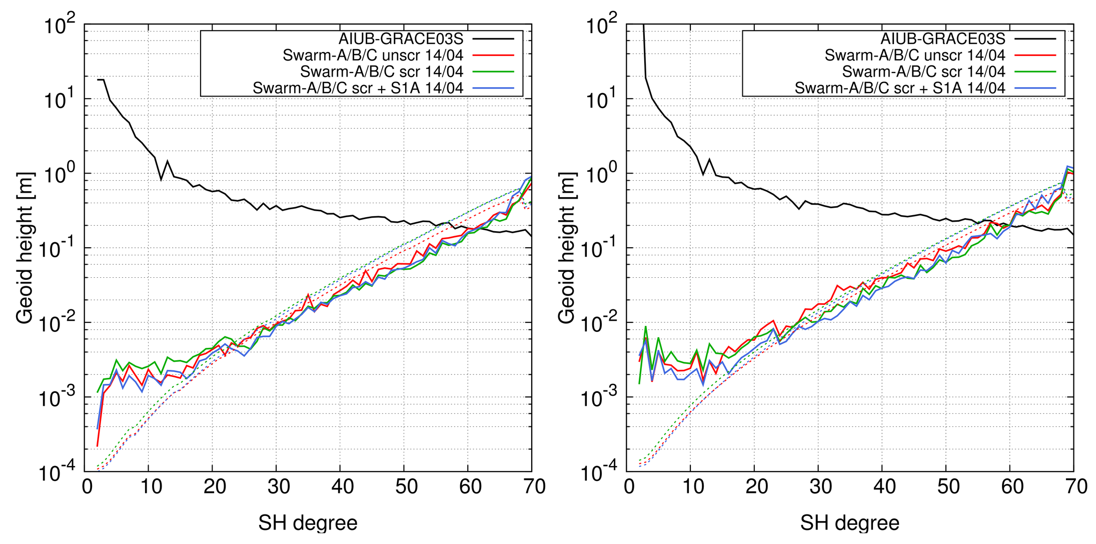


Figure 5: Difference degree amplitudes (solid) and formal error degree amplitudes (dashed) of monthly gravity fields for April 2014 recovered from Swarm kinematic orbits computed from original (red) and screened (greed) GPS data, as well as of the combined Swarm/S1A monthly solutions (blue). For the left plot the coefficients most affected by a polar gap of 8° have been excluded, for the right plot all coefficients have been included.

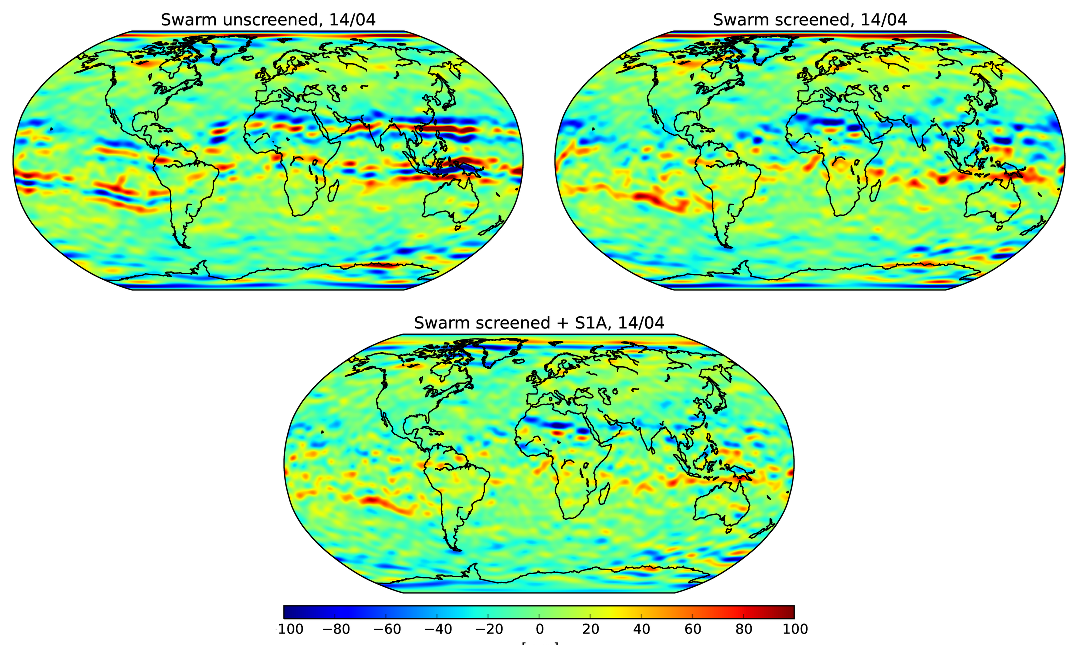


Figure 6: Geoid height differences w.r.t. AIUB-GRACE03S of a monthly gravity field derived from original Swarm (combined A/B/C) GPS data (left), screened Swarm GPS data (center), and screened Swarm and S1A GPS data (right) for April 2014. A 400 km Gauss filter has been appied.

Conclusions

S1A, S2A, and S3A kinematic orbits are shown to be of good quality and not affected by ionosphere-related artefacts along the geomagnetic equator. Despite the fact that they fly at higher altitudes than the Swarm satellites and that their Sun-synchronous orbits lead to larger polar gaps, Sentinel data is shown to significantly contribute to the lowest degrees of the Earth gravity field and capable of reducing degradations introduced by the data screening of Swarm GPS data during times of high ionospheric activity.

References

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